Atmospheric Science Research Priorities for Mars

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Background

This white paper is a collaborative effort from the Mars atmospheric science community in order to outline its scientific direction for the coming decade (2011-2020) to the Space Studies Board of the National Research Council. This paper addresses one component of a two-part approach to atmospheric exploration of Mars, divided along lines of surface lander (in situ) study (see Rafkin et al., 2009) and orbital exploration. Based upon solicited feedback from a wide range of contributors about the present and future direction of Mars atmospheric science, a consensus appears to be clearly emerging within the community, desiring a focus on three Science Investigation Areas (SIAs) for future (continued) study. Among the input received, the following were the three SIAs most commonly cited (in no particular order):

1. Development of a network of surface landers to provide global, diurnal and synoptic coverage of the near surface environment, including interactions at the planetary boundary layer (PBL).

2. Continued orbital observations of the basic atmospheric state (pressure, temperature, aerosol and water vapor abundance), to continue the long-term record of Mars Global Surveyor Thermal Emission Spectrometer (TES), Mars Express Planetary Fourier Spectrometer (PFS) and Mars Climate Sounder (MCS) on the Mars Reconnaissance Orbiter.

3. Development of a program for the observation of atmospheric trace gases (e.g. CH_4, SO_2) including spatial/temporal distribution and relevant photochemistry.

Discussion of SIA #1 (surface studies) is found in Rafkin et al., (2009), while SIAs #2 and #3 are discussed here. The discussion is divided into three sections, addressing the fundamental questions set forth by the SSB charter as they pertain to Mars atmospheric science:

1. What are the key scientific questions that will be driving Mars atmospheric science in the coming decade? What discoveries in the past decade have led us to these key scientific questions?

2. What progress can be made in the next decade to answer these questions?

3. What types of missions are necessary to obtain answers to these questions?

A sincere effort has been made to stress the points that are most <u>fundamental</u> to advancing the science in the coming decade. While there are many (countless??) scientific questions having great merit on their own, we deal here with those that will provide the greatest advancement for the community as a whole.

Question 1: What are the key scientific questions that will be driving Mars atmospheric science in the coming decade? What discoveries in the past decade have led us to these questions?

At the highest level, the 'key' scientific questions driving Mars atmospheric science into the next decade can be classified into two broad themes: atmospheric composition, which deals with the constituents of the atmosphere (both aerosol and gas) and their abundance and distribution, and atmospheric state, which addresses questions of atmospheric dynamics and evolution. We consider these each in turn.

Atmospheric Composition

Mars is unique among the terrestrial planets in that solid material plays a significant role in modifying its climate. Dust lifted from the surface interacts with the ambient radiation field, modifying the radiative environment of the surface and atmosphere, altering the thermal structure and changing the global circulation. There is seasonality to the martian dust cycle, with annually occurring periods of enhanced local and regional dust activity. Global dust events (GDEs) occur irregularly, but can envelop the entire globe with a thick cloud of dust in a matter of days (Cantor, 2007).

Recent modeling activity (Haberle et al., 2003, Basu et al., 2004) demonstrate a combination of convective processes (i.e. dust devils) and high threshold surface stress lifting as the "triggers" initiating the spontaneous and interannually variable GDEs. Once initiated, these storms can grow quickly over time. The causes of such growth, and the factors that discriminate between regional and global storms are unknown. Similarly, the means by which such events terminate are unidentified, but it has been suggested that a combination of particle settling and a change in the radiative environment introduced by the enhanced dust opacity itself (such that dust events may be self-limiting) may cause the ultimate demise of GDEs.

Limb profiles of dust abundance by TES (McConnochie and Smith, 2008) and the Mars Climate Sounder (MCS; Heavens et al., 2008) have resolved the vertical extent of dust in the atmosphere. Dust has been generally assumed to be well mixed in the lower atmosphere, with a rapid fall-off at higher altitudes (the so-called "Conrath" profile). This profile was (and is still) widely used by numerical models and for mission planning to simulate atmospheric dust profiles. The latest observations, however, have shown a more complex dust distribution that does not maintain the well-mixed character of the Conrath profile. Both TES and MCS are unable to capture behavior in the lowest (<5 km) regions of the atmosphere, precluding the ability to measure the vertical profile and depth of small-scale dust events. Establishing more representative dust profiles and dust abundances in the planetary boundary layer (PBL) will force reevaluation of standard circulation models to fit the improved observations, and thus facilitate better mission planning and protection of landed assets. Pertinent questions include:

What is the vertical distribution of dust during local/regional/global dust events?

What are the root causes behind initiation, growth and decay of global dust events? Why do some storms remain small and some grow to global scale?

Recent estimates of atmospheric water vapor column abundance by TES, Mars Reconnaissance Orbiter CRISM, and the Mars Express instruments (PFS, OMEGA, SPICAM), lead to a generally consistent picture of its seasonal and spatial distribution. The globally average abundance is about 10 prμm, but with significant enhancements at high northern latitudes (~60 prμm) and high southern latitudes (~30 prμm) during their respective summer seasons (Smith, 2004). While the northern summer maximum shows high repeatability from year to year, the southern summer maximum has been observed to vary in intensity by ~50% from year to year. Furthermore, the vertical distribution of water vapor through the atmospheric column remains largely unknown.

General circulation models (GCMs) still have significant difficulties reproducing the ebb and flow of the martian water cycle, which is attributed, in part, to the absence of a subsurface water reservoir to interact with the PBL. Orbital observations suggest up to a 10-20 prμm diurnal change in the vapor column, but models (e.g. Böttger et al., 2005) are able to attribute no more than 10% of that total to the adsorption of water vapor at the surface layer. This issue remains unresolved and will require a combination of surface and orbital observations to resolve. Despite, or perhaps because of, decades of observations of atmospheric vapor, there are many unanswered questions about the water cycle. Key among these are:

What is the abundance and variability of atmospheric water vapor on diurnal/seasonal/annual cycles? What factors contribute to these variations?

Is the water cycle a "closed" system, or is there secular transfer of water from one pole to the other through the atmosphere?

What is the role of the subsurface (regolith) on vapor abundance? What is the magnitude of the surface vapor flux on these timescales?

What is the vertical distribution of water in the atmosphere, both as vapor and ice?

Observations of Mars within the past decade have unequivocally identified the presence of methane in the martian atmosphere, though the source has not been identified as either biotic or abiotic, nor have discrete source regions been identified. The presence of methane, and potentially other reduced gases, indicates an atmosphere that is not stagnant, but rather presently active and changing. Additional observations (ground-based and orbital) have yielded basic distributions of ozone (Fast et al., 2006) and hydrogen peroxide (Encrenaz, et al., 2004), allowing preliminary validation of first-order photochemical models. Measurements by Mumma et al. (2009) reveal that methane varies on Mars with position and season, and provide a more convincing demonstration of the presence of methane than previous observations (Formisano et al., 2004; Krasnopolsky et al., 2004). This is a very surprising result since current photochemical models (e.g. Nair et al., 1994), which are successful in reproducing observations of atmospheric hydrogen- and oxygen-containing compounds, predict a 350-year lifetime for methane. However, the observed spatial and temporal variability suggests that the decomposition lifetime is much shorter.

Such a startling finding will undoubtedly serve as a catalyst for thorough reanalysis of martian atmospheric chemistry. As speculated by Mumma et al., (2009), the role of heterogeneous chemistry may be an important factor in the atmosphere that has, until recently, been neglected by the modeling community. Specifically, two roles for dust and aerosols seem promising. First, the lofting of soil and dust coated by strong oxidants may result in rapid decomposition of many atmospheric species, including methane. Second, electrochemical processes that take place in dust storms can alter the homogeneous chemistry balance. These processes (Atreya et al., 2006; Delory et al., 2006) have been speculated to be capable of efficiently producing hydrogen peroxide at levels up to 200 times the photochemically produced levels in the lower atmosphere. Little, however, is presently known about the electric fields on Mars. Questions concerning trace gases in the atmosphere therefore include:

What is the distribution and abundance of trace gases in the atmosphere (e.g. CH_4, O_3, SO_2)? What are the sources and sinks? Do they indicate the presence of life, currently or in the past? What role do subsurface activities play on controlling trace chemistry?

Is the composition of the atmosphere, both lower and upper, consistent with contemporary photochemical models? What does this tell us about processes (homogeneous or heterogeneous) that are missing?

Atmospheric State

There has been an improvement in our understanding of the dynamics and structure of the martian atmosphere in recent years, particularly from TES and MCS, but this knowledge has been largely limited to regions from 10-80 km, which can be observed readily from orbit (see Smith, 2008 and references therein). Numerical models, in conjunction with these observations, provide us with a reasonable approximation of the martian atmosphere at locations and times of day not observed, but also highlight deficiencies in understanding the behavior of the martian atmosphere.

The past decade has seen new observations covering the middle martian atmosphere (60-130 km) by both the MCS (<90 km) and MEX SPICAM (70-130 km) instruments, and the first incorporation of this data into GCMs (e.g., Forget et al., 2008; McDunn et al., 2008). While the dynamics of the middle and upper atmosphere are still rather poorly observed, vastly improved numerical models—the primary means of understanding the behavior of these regions—are now being put to bear on these problems. The first surface-to-upper-atmosphere numerical models (e.g. Angelats i Coll, 2005, González-Galindo et al., 2009) have been developed, and provide consistent model architecture at all levels. This is a significant step forward in modeling capabilities that will allow for more accurate modeling of the upper atmosphere. Aerobraking and entry, descent and landing density profile measurements (e.g. Withers and Smith, 2006) can provide limited sampling of the atmosphere at levels above 100 km, and appear consistent with model results. The upcoming 2013 MAVEN mission will begin to address this observational deficiency in part, but will also likely expose the true extent of our ignorance about the atmosphere, especially in the upper reaches. Indeed, the previous NRC Decadal Survey in 2003 (SSB, 2003) presented the following two questions as having the potential for pivotal scientific discovery: 'What are the dynamics of the middle and upper atmosphere of the planet?' and 'What are the rates of atmospheric escape?' These remain key unanswered questions going forward, and are augmented by the following supplemental queries:

What is the 4-D structure of the upper atmosphere, and how does it evolve with the solar cycle? How does the martian atmosphere interact with the solar wind?

How do processes in the upper atmosphere of Mars affect the lower atmosphere, and vice versa? How well do numerical models reflect this continuum of processes?

There is substantial geological and chemical evidence that early Mars had a much warmer and wetter environment than the present. There are broad indications of aqueous alteration of surface materials dated to the Noachian period (4.5-3.8 Ga), including the widespread presence of iron-rich phyllosilicate minerals mapped to the oldest, Noachian-aged surfaces (Bibring et al., 2006). Today, there is only limited evidence of recent liquid water at the surface, which is likely transient in nature, and neither widespread nor enduring. It is almost certain that the atmosphere has decreased in magnitude over martian history, but how did it do so? Is atmospheric erosion through loss to space responsible? Atmospheric erosion models can 'produce' multi-bar CO_2 atmospheres on early Mars that are consistent with today's thin atmosphere. Conversely, there are suggestions that much of the primitive atmospheric CO_2 has been converted into subsurface carbonates, and/or buried as CO_2 ice or CO_2-clathrate ice. Understanding the climate system as a whole (including the surface and subsurface environments) is key to extrapolating backwards to previous epochs, and presents us with several unanswered questions:

Are current erosion processes consistent with a substantially thicker early martian atmosphere that has progressively eroded to the present, thin state?

Could liquid water have been sustained at the surface during much of martian history?

What are the isotopic ratios of the most common gases? What does this tell us about atmospheric erosion rates and the possibility of life, past or present?

Is there an observable, secular or periodic change in martian climate (e.g. temperature, atmospheric opacity, water content) over extended periods?

There is surprisingly little observational data about martian winds, despite their critical importance in dictating the local composition and structure of the atmosphere, and their value for spacecraft safety. Descent profiles from past Mars surface payloads provide single profiles of wind, while the surface landers have provided qualitative measures of the surface winds over limited times. Observations of cloud and dust devil movement provide scarce, additional wind data. Knowledge of the wind field should be a critical component of any atmospheric survey. Surface layer winds regulate the flux of water vapor and heat into higher levels. Tropospheric winds yield information about such varied elements as the strength of the martian tides, state of the global circulation and vapor and trace gas transport. The importance of understanding the wind field is underscored by the efforts employed by spacecraft mission teams to constrain and understand the wind field for entry, descent and landing (EDL) of spacecraft. Current knowledge of the wind field for these purposes is obtained exclusively from numerical models (GCMs and mesoscale models), and, often times, such models yield vastly different wind profiles for the same locations. This underscores the need to have spacecraft data with which to validate the modeling assumptions being made. While models are useful for visualizing representative wind behavior, the absence of observational data ought to be corrected. Very basic questions concerning martian winds still remain, and include:

What is the 3-D wind structure of the martian atmosphere from the surface to upper atmosphere? How does it change with time of day? Season? Interannually?

What is the strength of the global circulation? How does it change with season?

Question 2: What progress can be made in the next decade to answer these questions? How?

Mapping the composition and state of the martian atmosphere can be accomplished in the coming decade by pursuing a three-pronged approach: 1) Characterizing boundary layer fluxes of atmospheric components, especially across the surface layer. This includes tracking the annual cycle of CO_2 into and out of the atmosphere at several surface locations, stable noncondensable gas (Ar and N_2) enrichment levels and the diurnal, seasonal and annual cycle of H_2O and trace gas exchange between the atmosphere and regolith. 2) Continued observations of the atmosphere from orbit to obtain global pressure, temperature and aerosol opacities from the surface to upper atmosphere, with good vertical resolution and time of day coverage. 3) Development of instrumentation (surface and orbital) for the detection of small amounts of trace gases and their isotopologues to the parts-per-trillion level.

Advances in modeling (i.e. GCM) capabilities will augment methods used to detect surface source locations of trace gases. Within the next decade, investigations designed to identify such source regions should be undertaken, as these will likely drive site selection for future landed missions. Data assimilation approaches (e.g., Lewis et al., 2007), still at a nascent stage, should help to improve the accuracy of GCMs by blending temperature and dust opacity data (derived from observed radiances) with model predictions. Better-validated models will also improve isolation of trace gas source regions.

Progress in understanding the 3-D wind field will be a challenging but necessary next step. For boundary layer winds, 3-D, high frequency surface measurements are ideally required, while for higher levels, winds can be extracted from remote sensing approaches. A combination of limb and nadir observations of dust storms is needed to more fully answer questions pertaining to the 3-D dust distribution, the growth and decay of storms and the transport of dust, water, and trace gases.

It is becoming clear many of these questions are not exclusive to the atmospheric community alone, and answering them will require the collaborative efforts of the broader Mars community. Interpreting the recent discovery of methane plumes, for example, is equally a problem of meteorology, geology and astrobiology. By treating Mars as a unified, and interconnected, system, we can best address these problems.

Question 3: What types of missions are necessary to obtain answers to these questions?

Measurements of surface fluxes should be a high priority investigation in the near future, and are most suited to surface landers, as the required (i.e. high-frequency) observations of the PBL are not possible from orbit. Discussion of surface observations, including the network lander concept is found in Rafkin et al., (2009).

To maintain a continuous seasonal climatology of temperature, dust, ice opacity, and the general atmospheric state, it is desirable to habitually fly instrumentation capable of regularly obtaining these data, which can be similar in capability and design to either TES or MCS, but should minimally include the means to observe in the dust, water ice and CO_2 absorption bands with moderate-to-high spectral resolution. Observations higher in the atmosphere, at levels where spacecraft aerobraking and aerocapture occur, are desirable as well, and instrumentation should be capable of providing, at minimum, measurements of atmospheric density. Such instruments must have both zenith and limb-scanning capabilities in order to provide both aerosol and thermal profiles and total column opacities. Better coverage in local time—an improvement over past and present observations—is needed to better characterize wave modes and diurnal variations of water vapor and ice clouds. These types of measurements should be baseline requirements for future missions, and can easily fly as a valuable component of a larger (e.g. New Frontiers, Flagship) payload.

The overarching goal of a future trace gas survey should be to seek atmospheric evidence for present habitability and life through a sensitive and comprehensive survey of the abundance and temporal and seasonal distribution of atmospheric species and isotopologues. To achieve the objectives of such a survey requires a coherent set of instruments, on both surface and orbital platforms, some with capabilities not previously flown to Mars. These should include remote sensing instrumentation with extremely high sensitivity to a broad suite of important trace gases combined with nearly continuous spatial mapping of key minor constituents and of atmospheric state including vertical profiles of atmospheric temperature and aerosol abundances. Atmospheric observations should include a baseline set of molecular species necessary to isolate the key photochemical, transport, condensation, and biogenic-geochemical processes that control the current chemical state of the Mars atmosphere. In many cases these observations will require exceptional sensitivities relative to prior mission capabilities. A near-circular, high-inclination orbit should be chosen to allow an optimum combination of global coverage, spatial resolution, and a rapid change of local time during the course of the mission. A lifetime of at least one martian year is necessary to observe the annual cycle, with the possibility of additional martian years highly desirable for assessing interannual variations.

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